Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Identification of the interacting force at the interface between primary-secondary structures

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ABSTRACT: In current seismic design, earthquake-induced vibrations of secondary structures are estimated solely from the accelerations of the primary structure. However, recent studies have shown that the response of the secondary structure interacts with the response of the primary structure. To accurately estimate the response of a secondary structure, the interacting force at the interface of the two structures needs to be considered. This force can be obtained from physical experiments incorporating the primary-secondary structure interaction. This paper focuses on the force development in a primary-secondary system. The secondary structure is placed on top of a fixed based primary structure. The responses in each subsystem were experimentally measured and the interacting force between the two was calculated. The results showed that the response of the primary structure is reduced substantially when the secondary structure is rigidly attached. However, the response of the secondary structure increases. The maximum interacting force is proportional to the ratio of the maximum acceleration at the base of the secondary structure to that at the top of the primary structure. It is, however, inversely proportional to the ratio of the maximum bending moment at the base of the two structures. A recommendation on the design of the degree of fixity for a secondary structure is presented.

1 INTRODUCTION

Secondary structures generally refer to all the non load-bearing elements in a structural system. Usually, secondary structures are not designed to resist external loads, e.g. earthquakes or impact loads. Thus, they are more prone to damage even under minor earthquakes where primary structures are likely to survive (e.g. Chen and Soong, 1988; Villaverde, 1996; Naito and Chouw, 2003).

The cost due to damage to the nonstructural components of buildings can easily exceed that of the primary components, both in terms of monetary and non-monetary loss (Ferner *et al.,* 2014). As a consequence, recent development in earthquake engineering research has put considerable effort into accommodating seismic resistance of secondary structures, mostly focusing on overturning prevention. The methods of preserving the secondary structures, however, are still inadequate. In practice, the floor response spectrum approach is often used, i.e. the response spectrum of the primary structure is applied as the loading of secondary structures in the same manner as the response spectrum of ground motions to the primary structure. With this approach, the primary-secondary structure interaction is neglected, and thus results in inaccurate prediction of the response of the secondary structure (Sackman and Kelly, 1979; Gillengerten, 2001).

Many past numerical studies have emphasised the significant correlation between the interacting forces at the primary-secondary structure interface and the response of the subsystems (Igusa and Kiureghian, 1985a,b; Asfura and Kiureghian, 1986). These forces depends heavily on the connection between the primary and secondary structures.

In this paper, secondary structures with different degrees of fixity are placed on top of a fixed based primary structure. The configuration is designed to experimentally obtain the horizontal force at the base of the secondary structure. The flexibility of the secondary structure was constrained by using compression springs. The effect of different degrees of fixity of the secondary structure on the response of each subsystem on the primary-secondary structure interaction is revealed. The correlation between the interacting force and the response of the secondary structure is also investigated. A recommendation on the design of the boundary conditions of secondary structures depending on their functions was proposed.

2 EXPERIMENTAL SETUP

2.1 Prototype and scaled model

The primary structure used in the experiment was an elastic fixed-base single degree-of-freedom (SDOF) frame model. The model represented the fundamental mode of a four-storey building prototype with 1:15 scale. The primary structure has an effective height, h_p of 575 mm and lumped mass, m_p of 57 kg. The fundamental frequency, f_p and damping ratio, ξ_p were 1.51 Hz (T = 0.662 s) and 4.8%, respectively. The beam of the primary structure is considered rigid.

A secondary structure with a roller support was placed on top of the primary structure (see Figure 1). The sliding support was simulated using a set of near-frictionless linear guide rails. A small carriage, on which the secondary structure is bolted, was able to slide freely on top of the guide rails. Compression springs were installed between the ends of the carriage and fixed on the primary structure.

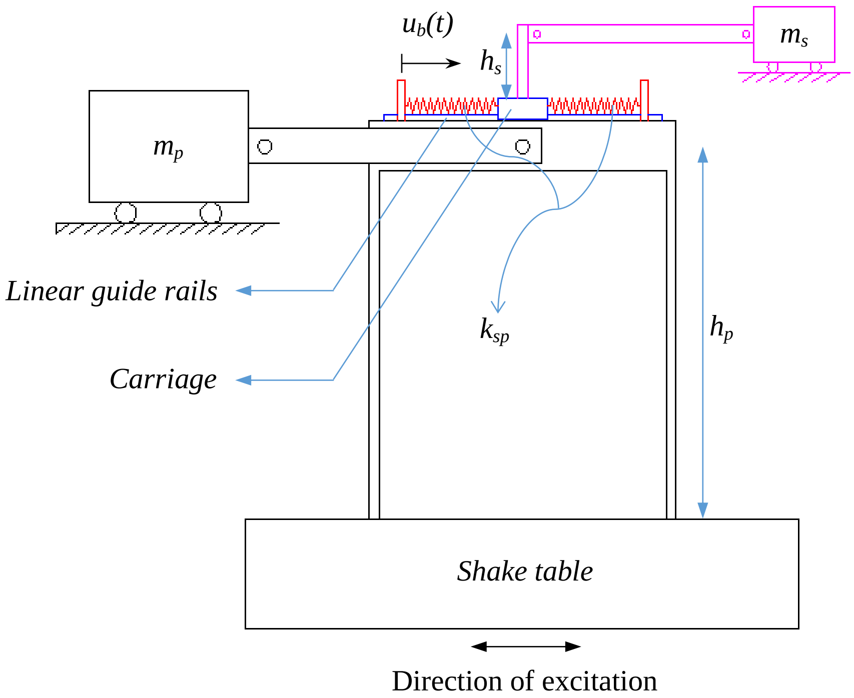

Figure 1. Experimental model of the primary-secondary system

The total displacement of both springs relative to the primary structure, $u_b(t)$ was measured using a laser displacement transducer. The collective stiffness of the two springs, k_{sp} was predefined and experimentally validated. The shear force at the primary-secondary structure interface, denoted herewith as F_h, can be calculated using the Equation 1.

$$F_h(t) = k_{sp} \times u_b(t) \quad (1)$$

The secondary structure has a total height, h_s of 45 mm and lumped mass, m_s of 1.889 kg. The fundamental frequency, f_s and damping ratio, ξ_s were 10 Hz (T = 0.1 s) and 9.23%, respectively. The deformation of the primary and secondary structures were measured in terms of bending moments using strain gauges attached at the lower end of the respective columns. The accelerations at the footing and at the top of the secondary structure were also measured.

Four different cases were considered: Primary structure without secondary structure (Case S0), those with a secondary structure supported by a slider connected to springs with low (Case S1) and high (Case S2) spring stiffness, and that with a fixed base secondary structure (Case S3), i.e. the secondary structure was prevented from sliding. The spring stiffness values for Case S1 and S2 are 275 N/m and 1732 N/m, respectively.

2.2 Ground motions

The earthquake simulation was performed using a shake table. The primary structure was bolted onto the shake table to ensure a fixed-base condition. The earthquake excitation used was simulated based on the Japanese design spectrum (JDS) for a hard soil condition (JSCE, 2000; Chouw and Hao, 2004). The target spectrum and the corresponding response spectrum of the excitation shown in Figure 2(a) have been scaled 1:15 to match the scale of the model. The scaled time history of the ground motion is presented in Figure 2(b).

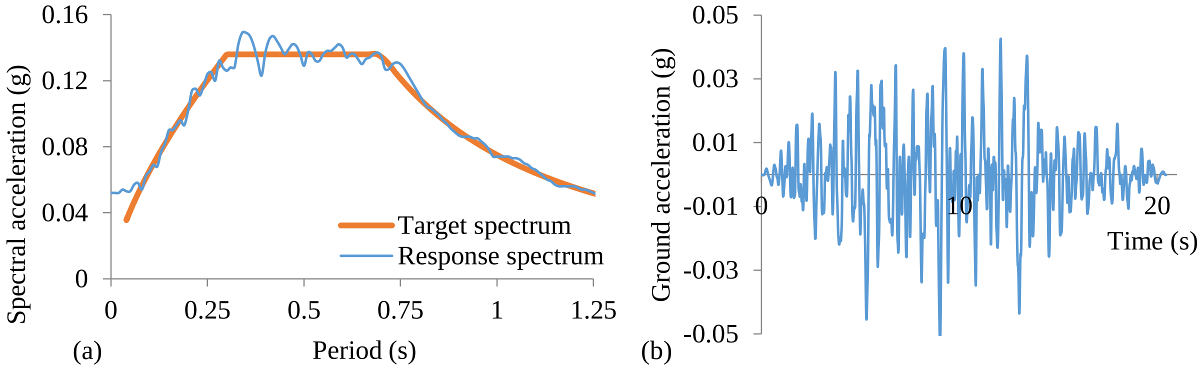

Figure 2. Earthquake excitation (a) Target and response spectra, and (b) Time history

3 RESULTS AND DISCUSSION

3.1 Deformation of the subsystems

The deformation of the primary structure for all four cases due to the selected ground motion is shown in Figure 3. In general, the primary structure deforms largest when there is no secondary structure. When a secondary structure is introduced to the system, the bending moment in the primary structure (BM_P) decreases. This result agrees with the findings from previous experimental studies performed by the authors (Lim and Chouw, 2014).

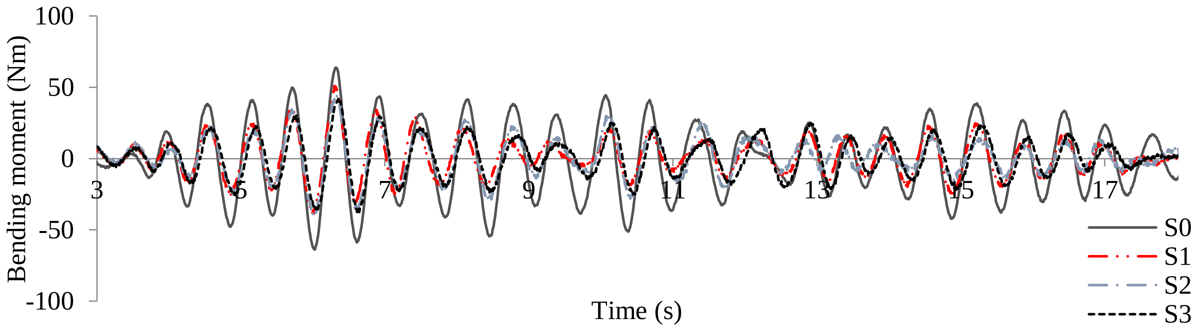

Figure 3. Reduction of bending moment in the primary structure due to the secondary structure with different boundary condition

Figure 3 shows that the stronger the fixity of the secondary structure, the larger the reduction in the deformation of the primary structure. The maximum BM_P were 63.82 Nm, 50.96 Nm, 45.08 Nm, and 41.87 Nm, for Cases S0, S1, S2, and S3, respectively.

On the other hand, the bending moment in the secondary structure (BM_S) is lowest when the secondary structure has weaker fixity. For the considered case, this result is anticipated, as the earthquake energy induced into the secondary structure is isolated with larger displacements due to more flexible springs. The maximum BM_S were 0.087 Nm and 0.188 Nm in the cases where it of flexible and stiff springs, respectively. When the secondary structure was rigidly fixed on the primary structure, the maximum BM_S was the largest, i.e. 0.206 Nm.

3.2 Acceleration of the secondary structure

The acceleration at the footing of the secondary structure (a_f) is shown in Figure 4. The acceleration is higher in the case of the flexible springs, i.e. the base of the secondary structure is allowed to translate more flexibly. As the stiffness of the support increases, the acceleration decreases until it eventually matches with the acceleration at the top of the primary structure when fixed base secondary structure was considered. The maximum a_f for S1, S2, and S3, were 0.218 g, 0.138 g, and 0.118 g, respectively. For comparison, the maximum acceleration of the primary structure (a_P) for Cases S0, S1, S2, and S3 were 0.173 g, 0.137 g, 0.09 g, and 0.118 g, respectively.

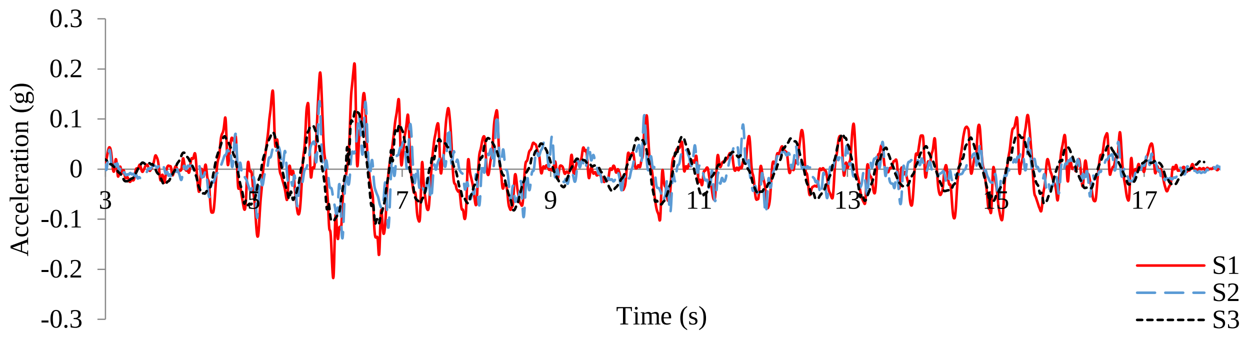

Figure 4. Acceleration at the footing of the secondary structure for different cases

Figure 5 shows the acceleration at the top of the secondary structure (a_t), with the maximum values of 0.212 g, 0.160 g, and 0.267 g, for S1, S2, and S3, respectively. The relative acceleration in the secondary structure, i.e. difference between the acceleration at the top and the footing, is highest for S3 and lowest for S1. High relative acceleration implies high relative movement within the secondary structure. Thus, for acceleration-sensitive secondary structures, the effect could be detrimental.

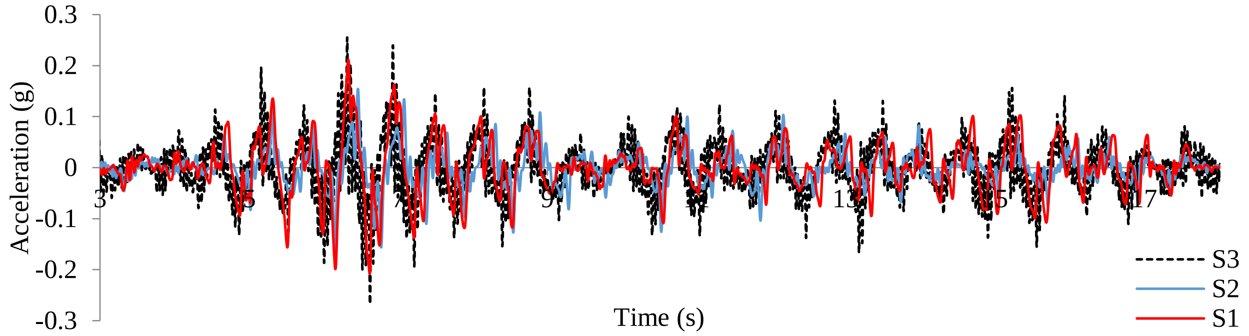

Figure 5. Acceleration at the top of the secondary structure for different cases

3.3 Interacting force at the interface

The interacting force at the interface is quantified in terms of the shear force of the secondary structure, which is calculated using Equation 1, as shown in Figure 6.

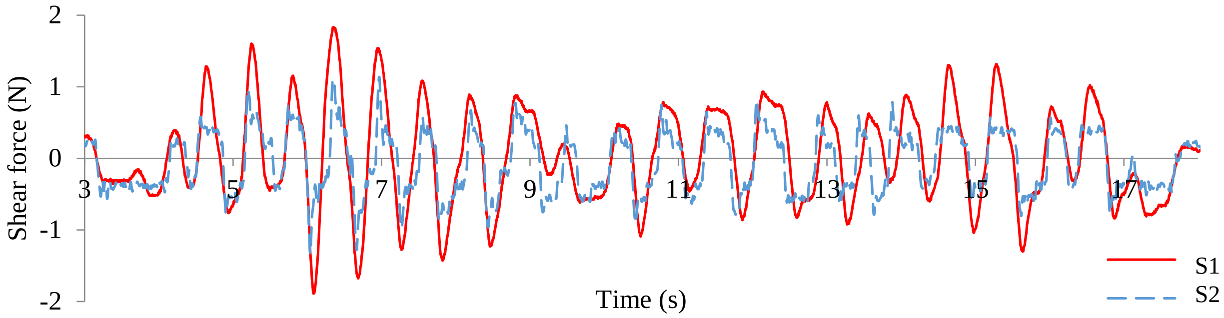

Figure 6. Comparison of shear force exerted at the primary-secondary structure interface in S1 and S2

The maximum displacements of the springs relative to the primary structure, $u_{b\max}$ were 6.88 mm and 0.77 mm, for the flexible and stiff springs. Despite the significant difference in the displacement values, due to the large difference in the spring stiffness, the maximum shear forces exerted in the two cases were considerably closer, i.e. 1.89 N and 1.34 N, in S1 and S2, respectively.

The maximum values of the the interacting force, $\boldsymbol{F_h}$ and the response of each subsystem is presented in Table 1. The interacting force is proportional to the ratio of acceleration at the footing of the secondary structure to the acceleration at the top of the primary structure and is inversely proportional to the secondary-primary structures bending moment ratio.

Table 1. Relationship between maximum interacting force and structural responses

Case	k_{sp} (N/m)	BM_P (Nm)	BM_S (Nm)	$\frac{BM_S}{BM_P}$	a_P (g)	a_f (g)	a_t (g)	$\frac{a_f}{a_P}$	u_b (mm)	F_h (N)
S0	--	63.82	--	--	0.173	--	--	--	--	--
S1	275	50.96	0.087	0.00171	0.137	0.218	0.212	1.58	6.88	1.89
S2	1732	45.08	0.188	0.00417	0.090	0.138	0.160	1.53	0.77	1.34
S3	--	41.87	0.206	0.00492	0.118	0.118	0.262	1	N/A	N/A

4 CONCLUSIONS

This paper discussed the response of the primary and secondary structures due to different boundary condition of the secondary structure. The experimental results revealed that,

- The deformation of the primary structure is reduced more significantly when a secondary structure is rigidly fixed on top of the primary structure compared to those with weaker fixity.
- The deformation of the secondary structure is smallest when the secondary structure is supported by flexible springs as the earthquake induced energy is partially isolated from the displacement occurred at the support.
- The relative acceleration between the top and footing of the secondary structure is highest for fixed base case, and lowest in the case of a more flexible support.
- The interacting force is proportional to the acceleration ratio between the secondary structure and the primary structure at the interface, and inversely proportional to the corresponding bending moment ratio.
- Depending on the function of the secondary structure, the boundary condition could be beneficial or detrimental. For instance, for acceleration-sensitive secondary structure, flexible roller support is more favourable. On the other hand, to reduce the deformation of the primary structure, a rigid fixed base should be preferred.

ACKNOWLEDGEMENT

The authors would like to thank the Ministry of Business, Innovation and Employment through Natural Hazards Reseach Platform for the support of the research under the Award UoA 3703249 with a scholarship for the first author.

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